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A 5000 year record of carbon sequestration from a coastal lagoon and wetland complex, Southern California, USA

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Abstract

Coastal wetlands have the potential to accumulate C at high rates over long time periods because they continuously accrete and bury organic-rich sediments, giving soils in coastal wetlands a distinct advantage over many other environments in the sequestration of organic C. Given that coastal wetlands are being lost worldwide, it is important to understand their C sequestration potential. Sediments in a southern California, USA coastal lagoon–wetland complex were cored, and depositional environments were interpreted. Suitable materials were radiocarbon dated. Bulk density and organic C were grouped by depositional environments, and average mass of C per unit volume and C accumulation rates in each depositional environment were calculated. The total organic C sequestered and rates of sequestration in each depositional environment were in the following order from most (fastest) to least (slowest): lagoon, intertidal, salt marsh, freshwater marsh, aeolian. This study demonstrated that high levels of organic C are sequestered per unit volume of sediment (35.9 ± 3.2 kg m^{-3}), and the mean rate of C accumulation was high (0.033 ± 0.0029 kg C m^{-2} year^{-1}) over a long time period (5000 years). Results of this study strongly demonstrate the importance and necessary high priority for preserving and restoring coastal wetlands both in the USA and internationally. However, despite their excellent potential to sequester C, significant losses of coastal wetlands are occurring in the United States and elsewhere in the world.

Keywords: Carbon sequestration; Coastal wetlands; Southern California

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1. Introduction

It is now widely believed that anthropogenic additions of CO_2 to the atmosphere are contributing to increased mean global surface temperatures, a phenomenon known as the "greenhouse effect" (Mosier, 1998; Bluemle et al., 1999). The largest terrestrial C pool is in soil, which contains an estimated 1550 Pg of organic C and 1700 Pg of inorganic C, compared to 550 Pg of C in biota and 750 Pg of C in the atmosphere (Lal et al., 1995).

Plants can remove CO_2 from the atmosphere to create carbohydrates, some of which are incorporated into plant tissues. As plants and plant parts die, some of these tissues are added to the soil as soil organic matter (Lal et al., 1998). Given the proper conditions, some soils can become net C sinks (Mosier, 1998). Because CO_2 can be removed from the atmosphere by the soil–plant system, interest in soil C sequestration is increasing. Much research has focused on increasing soil organic C content by altering agricultural management practices. However, insufficient attention has been given to the potential role of coastal wetlands in the sequestration of C. Agricultural soils are rapidly saturated

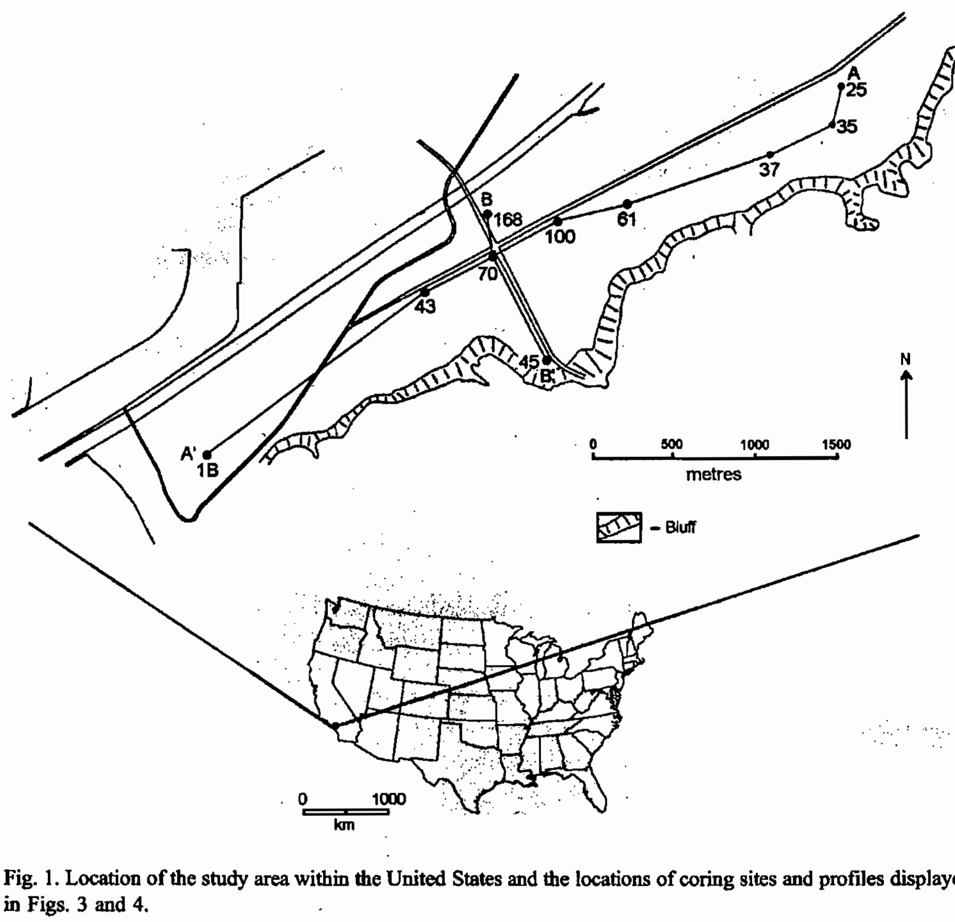

Fig. 1. Location of the study area within the United States and the locations of coring sites and profiles displayed in Figs. 3 and 4.

with C (Mosier, 1998), and significant C was previously released from agricultural soils by mechanized agriculture (Schlesinger, 1995), whereas coastal wetlands have the potential to sequester C continuously over thousands of years.

Coastal wetlands are areas with high net primary production (Barnes, 1980; Howes et al., 1985), and, in Maryland (Rabenhorst, 1995) and Florida (Choi et al., 2001), USA and New Brunswick, Canada (Connor et al., 2001), their soils and sediments sequester C at high rates. In addition, Grossman et al. (1998) have shown that, where sedimentation rates are high, organic C may be sequestered at depths greater than those typically sampled during soil studies. Coastal salt marshes release much smaller amounts of greenhouse gases, such as CH_4 and N_2O, than freshwater wetlands (DeLaune et al., 1990; Bartlett and Harris, 1993), so each unit of C sequestered in coastal marsh soils should have a greater impact in reducing global warming than the same unit of C sequestered in freshwater wetlands (Connor et al., 2001). Despite the apparent potential coastal marshes have for sequestering C, there have been very few C sequestration studies in coastal marshes. To help address this, we investigated C sequestration over the last 5000 years in a coastal lagoon–wetland complex located within the Los Angeles, CA, USA metropolitan area (Fig. 1).

2. Materials and methods

The site chosen for this study is a 440.2 ha property known as Ballona (Fig. 2). Los Angeles has a Mediterranean climate regime with an average annual temperature of about 19 °C and average annual rainfall of 37.5 cm (NOAA, 2001). Ten cores were drilled to depths of 6.25–17.0 m at the sites shown in Fig. 1. Cores were collected with a 7.6-cm diameter, 1.5-m-long split spoon in a hollow stem auger and stored in cardboard core boxes to await detailed description and sampling.

To indicate paleoenvironments, descriptions focused on texture, color, fossil remains, sedimentary structures, presence or absence of carbonates and other salts, and presence or absence of oxidized root channels. Organic C was determined in 106 samples with a LECO CHN-600 using the total combustion technique (Soil Survey Staff, 1996); the samples were randomly selected from the depositional environments represented in the cores. Samples containing calcium carbonate were treated with excess dilute HCl to remove inorganic C prior to combustion (Pulleman et al., 2000). Bulk density was determined for 56 samples using the paraffin-coated clod method (Blake and Hartge, 1986); these samples were also randomly selected from the depositional environments represented in the cores. The average mass of C per unit volume of sediment in each depositional environment was calculated by multiplying the average organic C content by the average bulk density.

Shells, charcoal, wood, and peat were sampled and submitted to Beta Analytic (Miami, FL) for radiocarbon analysis. Shell dates were corrected for the reservoir effect as described by Talma and Vogel (1993) using the calibration database of Stuiver et al. (1998). Radiocarbon dates were then used to estimate the depth of the 5000 year BP level in all cores containing datable material, assuming sedimentation rates were constant for the interval between any two radiocarbon dates. This cutoff date was chosen because all the

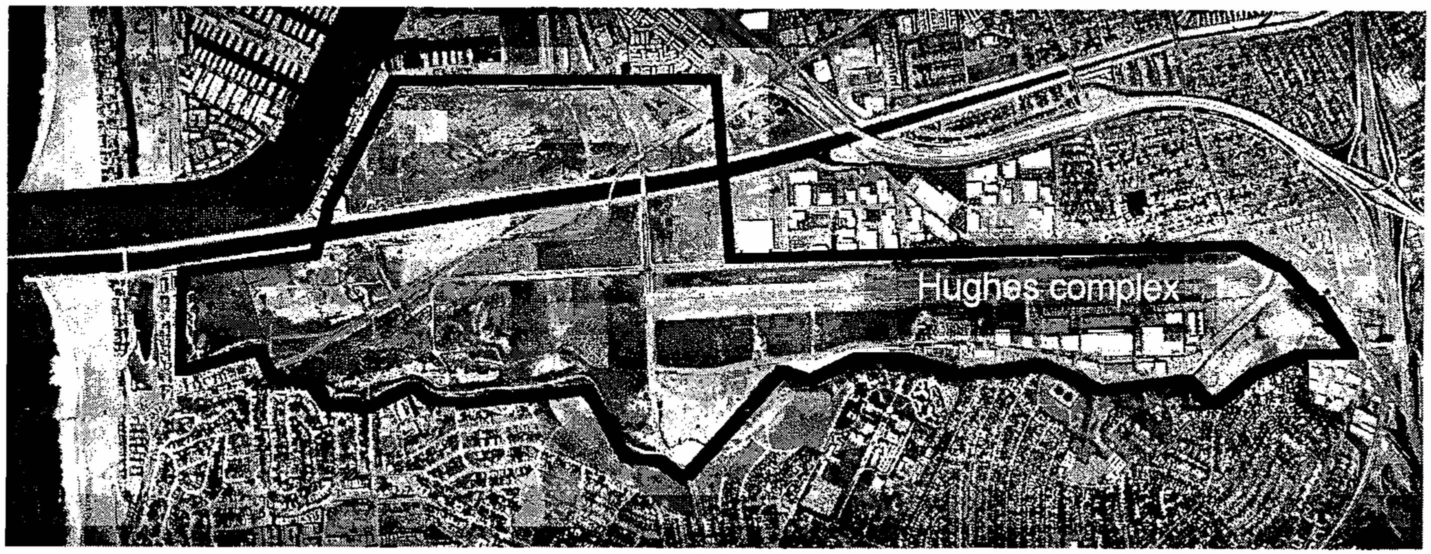

Fig. 2. Aerial photograph of the study site. The area included in the study is outlined. The east end of the property, labeled "Hughes complex" and located roughly between Cores 25 and 61 as shown on Fig. 1, includes a runway and buildings used for the manufacture of aircraft beginning circa World War II. More recently, Hollywood has used some of the hangers as sets for shooting movies. The west end of the property is only lightly developed with some roads and pads for oil wells. The Pacific Ocean can be seen on the west edge of the photo and metropolitan Los Angeles can be seen surrounding the study site.

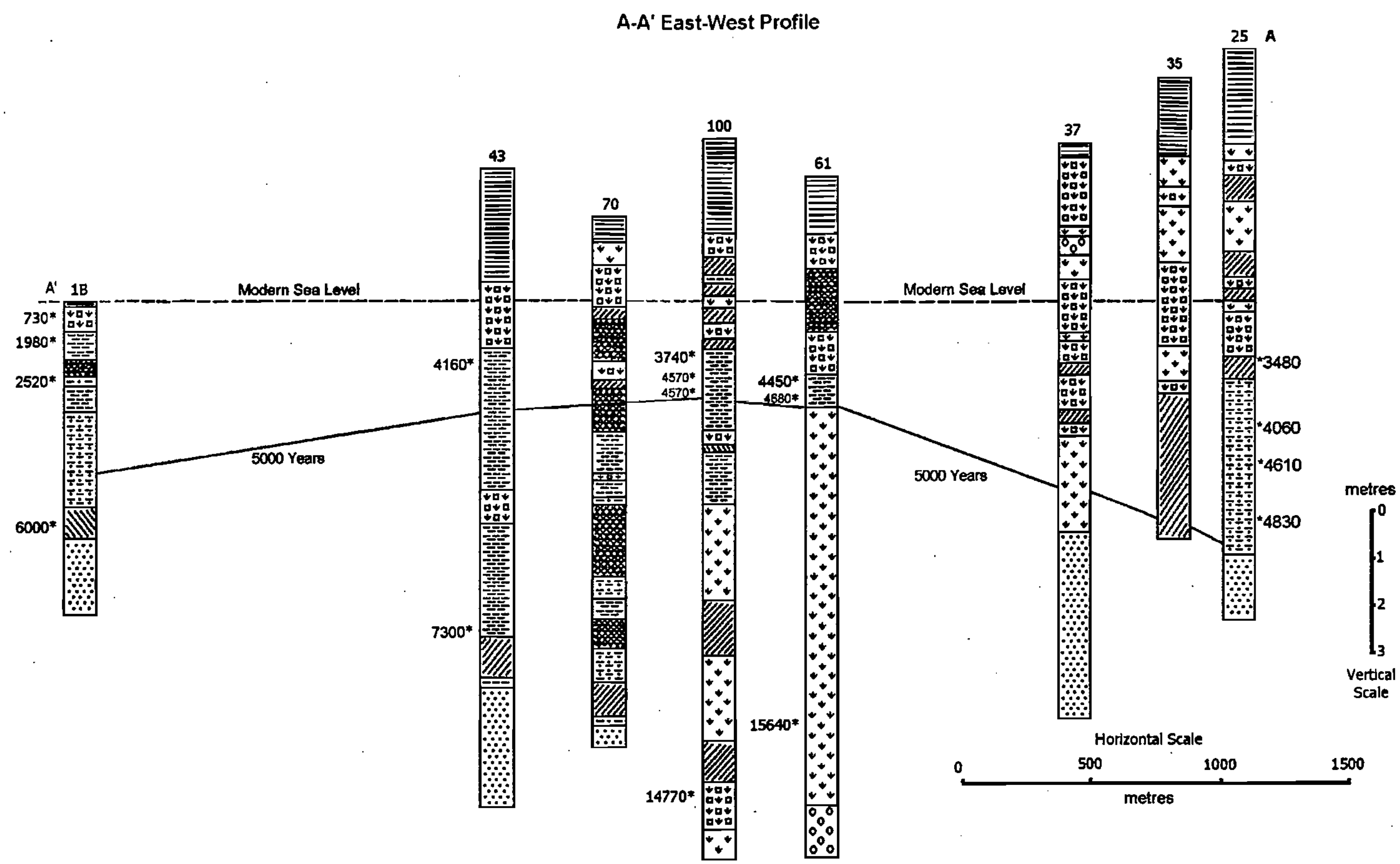

Fig. 3. The depositional environments in each core, the location of each radiocarbon date (shown by * and date), and the position of the 5000 year BP level in the A–A′ transect. For key to the depositional environments, see Fig. 4.

cores covered the last 5000 years, although some contained much older sediments. Dates were then projected between dated cores. None of the cores in the B–B′ transect contained datable material, so the 5000 year BP depth projected between Cores 43 and 100 in the A–A′ transect was used for the cores in the B–B′ transect. This was thought to be reasonable because in the A–A′ transect, the 5000 year BP level occurs at nearly the same depth in Cores 43, 61, and 100, all of which are close to the remaining cores in the B–B′ transect. Radiocarbon dates were also used to calculate sedimentation rates for Cores 1B, 25, 43, 61, and 100.

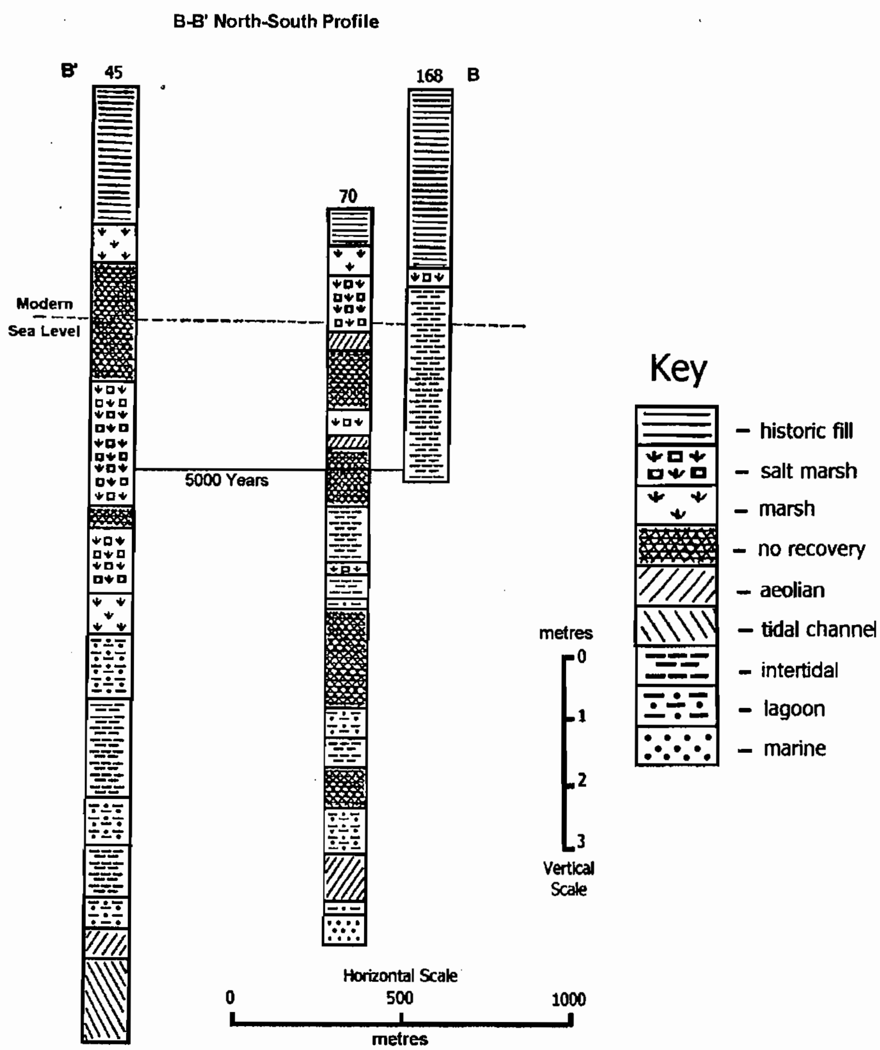

Fig. 4. The depositional environments in each core and position of the assumed 5000 year BP level in the B–B′ transect.

Table 1
Summary of radiocarbon dates obtained for the study

Core	Depth interval (m)	Material dated	C13/C12 (‰)	Age (BP)	Laboratory sample number
1B	0.43	charcoal	−27.2	730 ± 60	Beta-131129
1B	0.84	charcoal	−25.2	1980 ± 60	Beta-131130
1B	1.69	hornshell (*C. califorinica*)	−2.7	2520 ± 50	Beta-131131
1B	4.83–4.88	oyster (*O. lurida*)	+1.5	6000 ± 90	Beta-131132
25	6.65	wood	−28.3	3480 ± 70	Beta-131133
25	8.05	charcoal	−30.8	4060 ± 80	Beta-131134
25	8.99	charcoal	−28.5	4610 ± 60	Beta-131135
25	9.57	charcoal	−28.9	4830 ± 60	Beta-131136
43	4.17–4.30	hornshell (*C. califorinica*)	−0.5	4160 ± 70	Beta-124363
43	9.95–9.98	chione (*Chione* sp.)	−2.4	7300 ± 100	Beta-124364
61	4.32–4.57	hornshell (*C. califorinica*)	−5.7	4450 ± 70	Beta-124365
61	4.74–4.80	hornshell (*C. califorinica*)	−0.8	4680 ± 140	Beta-124366
61	11.89–11.92	peat	−24.8	15,640 ± 50	Beta-124367
100	4.60–4.75	hornshell (*C. califorinica*)	−2.9	3740 ± 70	Beta-124368
100	5.08–5.13	oyster (*O. lurida*)	−2.5	4570 ± 130	Beta-124369
100	5.27–5.30	oyster (*O. lurida*)	−0.2	4570 ± 70	Beta-124370
100	14.16–14.37	wood	−25.7	14,770 ± 120	Beta-124371

The length of each uniform depositional environment was measured down to the 5000 BP level, as was the total depth to this level in each of the 10 cores. As some segments of core could not be recovered, gaps in the cores were split equally between the depositional environments above and below. If the same depositional environment was interpreted on both sides of the gap, that depositional environment was assumed to continue through the gap. The percent of each depositional environment shown by the cores was assumed to represent the percentage throughout the study area. To estimate the volume of sediment deposited since 5000 BP, the area of the site (440.2 ha) was multiplied by the average sediment thickness to the 5000 years BP level excluding anthropogenic deposits of historic fill. The contact between historic fill and the underlying sediments was assumed to represent 0 years BP, as most development involving the use of fill at the site has been industrial and occurred about the time of World War II (Fig. 2). The volume of sediment accumulated in each depositional environment was determined by multiplying the percent of each environment by the total sediment volume. The average organic C accumulation

Table 2
Average organic carbon, bulk density, and mass of C values for each depositional environment

Environment	Organic C (%)			Bulk density (kg m^{-3})			Organic C (kg m^{-3})	
	n	Mean	S.D.	*n*	Mean	S.D.	Mean	S.D.
Salt marsh	29	2.82	2.57	14	1536	176	43.3	4.5
Marsh	23	1.28	0.92	10	1718	114	22.0	1.0
Intertidal	21	3.08	2.82	12	1455	169	44.8	4.8
Aeolian	19	0.67	0.62	10	1435	103	9.6	0.6
Lagoon	14	3.83	2.66	10	1499	136	57.4	3.6

Table 3
Total organic carbon in the Ballona study site, organic carbon by depositional environment, and rates of organic carbon accumulation

Environment	% Area	Total area (m^2)	Volume (m^3)	Organic C ($kg\ m^{-3}$)		kg Organic C		kg C $m^{-2}\ year^{-1}$	
				Mean	S.D.	Mean	S.D.	Mean	S.D.
Salt marsh	38.3	1.69×10^6	7.66×10^6	43.3	4.5	3.32×10^8	3.45×10^7	0.039	0.0041
Marsh	18.9	8.32×10^5	3.80×10^6	22.0	1.0	8.36×10^7	3.80×10^6	0.020	0.0009
Intertidal	16.4	7.22×10^5	3.30×10^6	44.8	4.8	1.48×10^8	1.58×10^7	0.041	0.0044
Aeolian	15.5	6.82×10^5	3.12×10^6	9.61	0.6	3.00×10^7	1.87×10^6	0.009	0.0005
Lagoon	11.0	4.84×10^5	2.21×10^6	57.4	3.6	1.27×10^8	7.96×10^6	0.052	0.0032
Total		4.40×10^6	20.1×10^6			7.21×10^8	6.39×10^7	0.033	0.0029

Organic C concentrations are from Table 2.

rate was calculated by dividing the total organic C in the sediment deposited since 5000 BP by the area of the site (440.2 ha) and the elapsed time (5000 years).

3. Results

The depositional environments interpreted for each core, the positions of the materials dated, and the radiocarbon dates obtained are shown in Figs. 3 and 4. The materials dated are summarized in Table 1, and mean organic C and bulk density values for each depositional environment are given in Table 2. The average values for mass of organic C per m^3 of sediment shown in the final column of Table 2 were used to calculate C sequestration. Over the last 5000 years, sediments on the site accumulated to an average depth of 4.57 m. Assuming this value is representative of the entire 440.2 ha, the total sediment volume in the study area is approximately $20.1 \times 10^6\ m^3$. The percent area of each depositional environment and their corresponding areas and volumes are given in Table 3. Table 3 also shows the amounts of organic C sequestered in each depositional

Table 4
Sedimentation rates at the Ballona site

Core	Interval (m)	Vertical distance (mm)	Time interval (year)	Time (year)	Sedimentation rate (mm $year^{-1}$)	Dominant environment(s)
1B	0.84–0.43	410	1980–730	1250	0.328	salt marsh
1B	1.69–0.84	850	2520–1980	540	1.574	intertidal
1B	4.86–1.69	3170	6000–2520	3480	0.911	lagoon
25	8.05–6.65	1400	4060–3480	580	2.414	lagoon and aeolian
25	8.99–8.05	940	4610–4060	550	1.709	lagoon
25	9.57–8.99	580	4830–4610	220	2.636	lagoon
43	9.97–4.24	5730	7300–4160	3140	1.825	intertidal
61	4.77–4.45	320	4680–4450	230	1.391	intertidal
61	11.91–4.77	7140	15,640–4680	10,960	0.651	marsh
100	5.29–4.68	610	4570–3740	830	0.735	intertidal
100	14.27–5.29	8980	14,770–4570	10,200	0.880	marsh/aeolian/intertidal

environment, the total organic C sequestered over the whole site, rates of C sequestration by depositional environment, and the mean rate for the whole site. Sedimentation rates at the site are given in Table 4.

4. Discussion

Carbon sequestration within a depositional environment is related to biomass production; C cannot be sequestered if biomass is not being produced and subsequently buried. Barnes (1980) reported relative biomass production in coastal lagoon–wetland complexes as: marshes < salt marshes < lagoons, with some overlap in productivity between these environments. We found the following trend in organic C sequestration values: aeolian < marsh < salt marsh < intertidal < lagoon (Table 2) with overlap in the values, giving a sequence similar to that reported by Barnes (1980).

The average organic C content (35.9 kg m^{-3}, range 9.6–57.4 kg m^{-3}) of the sediments at the Ballona site is nearly three times greater than the mean values of 12.6 kg m^{-3} (range 1.7–49.1 kg m^{-3}) for the soils of Washington, Oregon, and Idaho reported by Kern et al. (1998) and of 13.6 kg m^{-3} (range 2.3–88.2 kg m^{-3}) for the soils of western Oregon reported by Homann et al. (1998). It is also much greater than the average of 16.8 kg m^{-3} (range 9.3–40.6 kg m^{-3}) reported by Tarnocai (1998) for soils in Canada and the average of 7.4 kg m^{-3} (range 4.0–9.6 kg m^{-3}) for soils in western Nigeria (Lal, 1998). The high organic C values at the Ballona site also extend to much greater depths than in terrestrial soils; some of the cores with radiocarbon ages exceeding 14,000 BP extend to depths of 17 m and have similar organic C values throughout with no decline in organic C with depth. Organic C has therefore been sequestered in these environments at high rates for long periods of time. In contrast, the soil values reported above refer almost entirely to the upper metre of soil because the organic C in most soils is contained mainly within this layer (Eswaran et al., 1995). In soils of the American Midwest, for example, it takes >1000 years for an A horizon to extend by 2.5 cm at a depth of 1 m (Troeh et al., 1999). Consequently, much more C has been sequestered per unit area in the coastal wetlands at Ballona than in the agricultural, forest, or grassland soils of the areas cited above.

On average, 0.03 kg C m^{-2} $year^{-1}$ has accumulated at the Ballona site over the last 5000 year BP (Table 3). Similar long-term rates of C sequestration have been estimated for coastal wetland soils (Rabenhorst, 1995; Connor et al., 2001) and for organic C burial rates in lakes and peatlands (Dean and Gorham, 1998; Turunen et al., 2001). Short-term accumulation rates may be much higher than this in some agricultural soils. For example, Neill et al. (1998) reported sequestration rates as high as 0.304 kg C m^{-2} $year^{-1}$ in the upper 0.5 m of a soil 5 years after conversion from forest to pasture. However, over a period of 81 years after the same land use change, rates in the same soil were only 0.022 kg C m^{-2} $year^{-1}$. Compaction, a common problem in modern mechanized agriculture, impedes C sequestration by soil (Brevik et al., 2002). Most agricultural soils sequester C for only a limited period, probably about 50–100 years after management changes are made (Mosier, 1998), so, unlike coastal wetlands, they are unlikely to sequester C at high rates for periods approaching 5000 years. In addition, future changes in management may cause sequestered C to be re-released from agricultural soils, a possibility that is less likely in coastal wetlands if they are protected.

This discussion does not imply that agricultural soils are not important sinks of organic C. The fact that these soils cover a much greater percentage of the Earth and are more easily managed than coastal wetlands makes them very important. It is meant to demonstrate that coastal wetlands sequester C very efficiently. Soils in coastal wetlands have a distinct advantage over many other environments for sequestration of organic C, in that they continuously accrete and bury organic-rich sediments (Rabenhorst, 1995; Connor et al., 2001) created by their typically high net primary production rates (Barnes, 1980; Howes et al., 1985). It is rare in most environments for long-term sedimentation rates to exceed 50 mm 1000 $year^{-1}$ (0.05 mm $year^{-1}$; Blatt et al., 1980). The lowest sedimentation rate at Ballona (0.328 mm $year^{-1}$) is approximately 6.5 times this value, and the highest sedimentation rate (2.636 mm $year^{-1}$) is over 50 times greater. The high sequestration rates of marshes also reflect anaerobic conditions that inhibit decomposition of organic materials (Troeh et al., 1999). An estimated 14.5% of the world's C sequestered in soils is stored in wetland soils, although wetlands only comprise about 4% of Earth's land area (Rabenhorst, 1995).

Despite their excellent potential to sequester C, coastal wetlands are rapidly disappearing. The United States has about 4.05×10^6 ha of coastal wetlands, with 40% found along the Louisiana coast alone (Groat, 1989). Over 80% of the Louisiana coast has shoreline erosion rates that exceed 6 m $year^{-1}$, with rates as high as 50 m $year^{-1}$ in some areas (Steyer and Stewart, 1992). Up to 100 km^2 of coastal wetlands have been lost from Louisiana each year (Groat, 1989) with a total loss of around 3900 km^2 (Boesch et al., 1994). Although most of the coastal wetland loss occurring in the United States is in Louisiana (Groat, 1989; Steyer and Stewart, 1992), significant loss has also occurred along other portions of the United States' Atlantic/Gulf of Mexico coast (Moorhead and Brinson, 1995; White and Morton, 1997). Coastal wetlands are less extensive on the Pacific coast of the United States, but >80% of those in California have been filled or dyked for agriculture, urban development, and salt production (Tsihrintzis et al., 1996). This problem is hardly unique to the United States. Significant areas of coastal wetlands have also been lost in China, The Netherlands, and along deltas of rivers such as the Nile and Niger, to name a few (Titus, 1991). The high rates of C sequestration in coastal marsh soils suggest that protection of existing coastal marshes and reclamation of areas already lost to anthropogenic activity should be made a high priority.

5. Conclusions

Sediments at the Ballona site contain relatively high concentrations of organic C which has accumulated at high rates over a long period of time. This is attributed to high net primary production in a coastal lagoon–wetland ecosystem that has served as an anaerobic sediment trap. The ability of coastal wetland systems to sequester C at high rates has now been demonstrated on both the Pacific and Atlantic coasts of North America. Coastal wetlands are much more efficient per unit area than terrestrial soils at sequestering C. One strategy that several countries have considered to meet their goals for reducing greenhouse gas emissions under the Kyoto Protocol is to provide credits for C sinks such as sequestration of C in soil (Marland et al., 1999). Because of their high C sequestration rates, preservation and restoration of coastal wetlands should be considered in any such strategy.

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